Maera: A Hybrid Wheeled-Legged Robot designed for Research and Education

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Abstract. In this paper, *Maera*, a low-cost open-source hybrid legged-wheeled robot, is presented. The robot is designed to be used as a teaching platform and a hands-on introductory example in the field of robotics. To this end, the paper describes in detail the design and manufacturing methods used, along with the main specifications and capabilities of the robot. Two educational use-cases are presented and evaluated by taking into account student feedback. It is shown how Maera can be used as a complete project that brings to the surface the most important topics in robotics, namely, design, dynamics, manufacturing, embedded systems, and control. Most importantly, it is described how the project bridges the gap between theoretical knowledge and practice throughout the development stages of a complex robotic application.

Keywords: Legged Robots, Educational Robotics, STEM Education, 3D Printing, Open Source, Low Cost

1 Introduction

In the rapidly advancing technological era, the field of robotics is experiencing accelerating growth. Statistics show that by the year 2023 the robotics market will have doubled in size, indicating a Compound Annual Growth Rate of 10.9% [1]. This growth raises the need to educate students in the field of robotics so that they can adapt to the involvement of robots in their career and everyday life. In addition, the introduction of robots in the education curriculum to assist with STEM, as well as non-STEM, subjects has proven to have great potential [2,3]. In the field of Engineering, robotics courses are taught at the undergraduate level, and more students are actively engaging in the design and control of robotic platforms. However, the knowledge acquired from university courses usually is at a theoretical level. It is essential that the students are able to apply the theoretical knowledge they gain to real-life applications.

To be able to do that, Additive Manufacturing (AM) methods can help significantly. Recently, AM machines have become more accessible and inexpensive.

Following the RepRap Initiative, prices of 3D Printers have been decreasing exponentially, finding their way in amateur makers' homes and various labs [4]. In addition to the ease of manufacturing functional parts, various robotics tools have become more accessible. Open-source microcontroller/computer boards, prototyping platforms, as well as off-the-shelf components and actuators, can be acquired at low cost. Clearly, a trend towards the decentralization of the production process is taking form. The above lay the ground for bridging the gap between STEM Education and Applied Sciences, by introducing the design and manufacturing of simple and low-cost robots to be used inside the classroom.

Recent years have shown extensive research in the field of legged robots, but little attention has been given to the educational value of such mobile robotic systems. Legged robots such as Spot Mini by Boston Dynamics [5], StarlETH [6] and ANYmal [7] by ETH, Cheetah by MIT [8], Jelly by UC Berkeley [9], etc., are robots that are mostly optimised for industrial purposes. Robots such as Stag Mk2 [10] and OpenDOG [11] are low cost and accessible, but are essentially hobby projects. Other platforms like Bobcat [12] and Cheetah-Cub [13] by EPFL are small and low cost, but are mainly focused on research purposes. Some educational legged robots do exist, such as the PUT Hexapod Family and the RMIT Walking Robots Family [14]. However, these robots are mostly arachnids, utilizing only quasi-static locomotion methods. Furthermore, a large number of educational robots on the website Thingiverse [15] exist, which are mostly focused on primary school teaching. To sum up, existing educational approaches focus on control methods and using wheeled and manipulator robots to accomplish various tasks, leaving aside the process of design and manufacturing, especially regarding legged robots.

In this paper, the hybrid robot *Maera* is presented as a teaching platform, combining wheeled and legged locomotion, thus highlighting the educational value of both types of mobile robots. *Maera* has been used as an educational tool during the DAAD Summer School, a joint project of the National Technical University of Athens (NTUA) and the University of Duisburg-Essen (UDE), and during a short educational event. The robot served the purpose of a hands-on example for various lectures and workshops. In this way, teaching various theoretical concepts through real-life hardware was possible; the outcomes of this work and experience are presented in this paper.

In Sect. 2 the proposed design is presented and the various mechanical and electronic components are documented. In Sect. 3 educational use-cases and the way *Maera* robot was utilized as a teaching platform are conferred. The student feedback is presented in the form of a Likert Scale Evaluation [16] and discussed in Sect. 4. The conclusion of this paper and future work are given in Sect. 5.

2 Maera Specifications: Designing for Education

The first step of the design process was to set guidelines aligned with our goal, i.e. to develop a mechatronic physical system, aimed to facilitate the understanding of complex theoretical concepts through an interactive hands-on learning activity. To this end, a set of specifications has been defined and is listed next. (a) To be an easy-to-use teaching platform. Therefore it must be designed in a way that it can be treated as an educational tool. (b) To incorporate both wheels and legs, to combine the advantages of the two most important locomotion mechanisms. (c) To be relatively small, so it can be carried around in the classroom or to short educational events. (d) To be relatively inexpensive to show that a fully functional robot can be built using off-the-shelf components and accessible manufacturing methods. (e) To incorporate different actuation technologies. The use of rotary and linear servos has been proposed to introduce the different advantages of using each actuation method. (f) To incorporate 3D printed parts so that the students can get acquainted with the technology as well as the various constraints when designing for AM. (g) To be easy-to-assemble so the whole procedure can be completed during one week long workshops. (h) To be modular so the students can test the effect each design parameter has on the robot's capabilities.

2.1 Hardware Architecture

Maera incorporates a number of actuation technologies and materials. The robot is based on a standard quadruped design, extended in a way to include actuated wheels at its toes. It features four two-segment 3D printed legs and a lightweight body frame consisting of 3D printed parts and two carbon fibre tubes as shown in Fig. 1. The 3D printer filament used is Acrylonitrile Butadiene Styrene (ABS) plastic due to its good mechanical properties and popularity as a printing material. The design is modular, in a way that several design parameters can be modified and that the effect each one has on its capabilities can be observed (payload capacity, stability, etc). Modules can also be added or removed (different microcontrollers, sensors, etc). Most of the parts are designed so they can be built using a 3D Printer and most of the components can be bought at a hobby store. The prototype robot has been built using mostly elements from an online shop [17]. *Maera* has been designed to be open-source. The part files are available upon contact with the lead author.

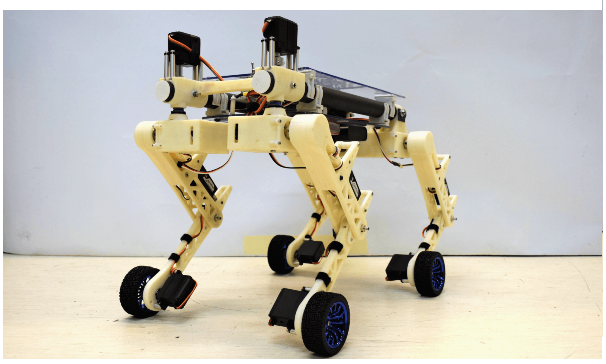
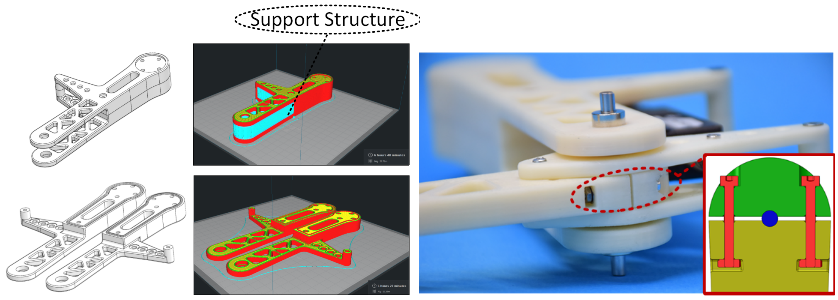


Fig. 1: *Maera*: A Hybrid Legged-Wheeled Robot.

The design of the current platform can be used as an example, assisting lecturers on teaching 3D Printing design principles. It is essential to teach students the limitations when designing for AM. One of the most challenging problems is the need for support structures when parts are built with a bottom-up approach. To tackle this constraint, one needs to cleverly adjust the designs to bypass the need for support structures. It is important to correctly orient the parts during the pre-processing stage or split the parts for post-printing assembly. By preparing the print jobs and orienting the parts themselves, students can understand the cost of using support structures in AM as shown in Fig. 2a.



(a) Split to Assembly.

(b) Nut Pockets.

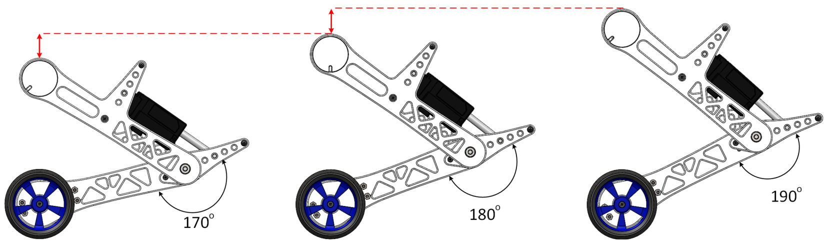
Fig. 2: 3D Printing Design Principles showcased using the robot *Maera*.

Other important design principles showcased by the platform itself, include joining methods suitable for 3D printed parts (such as nut pockets, Fig. 2b), as well as methods to orient the parts correctly, before printing, to receive tension loading. AM processes produce orthotropic parts, meaning that they display different mechanical properties along different axes. By preparing and printing the robot's legs, students can get acquainted with the importance of designing a part with layers parallel to the loading direction.

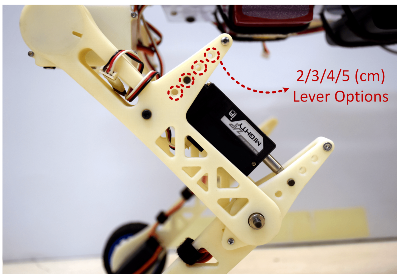
Another important aspect of teaching the principles of legged robots, concerns alternative actuation methods. Using this platform one can focus on the differences of using rotary and linear electric servo actuators. A rotary RC servo motor was used for actuating the hip joint and a linear actuator was used to actuate the knee joint. By using the servo motors, the students can realise the advantages of each method when actuating legged robots. For example, by placing the end effector of each leg below the corresponding hip joint during stance, students realise that the current consumption is close to zero (≈0.05A). This way one can showcase the advantage of actuating static loads with linear actuators that use lead screw-nut mechanisms. These mechanisms, due to their inner frictional forces, can hold static loads with the motors drawing almost zero currents. In our case, static loading occurs due to the weight of the robot while moving on wheels, making linear lead screw actuators perfect candidates. On the downside, such systems have lower efficiency (0.3-0.5), so while actuating dynamic loads different actuation methods (e.g. RC servos) are recommended.

In addition, *Maera* incorporates three core modular mechanisms. These can be used to change parameters of the robot and consequently affect its capabilities, or even add different modules, e.g different microcontrollers, sensors, etc. The basic modular mechanisms of the robot are the following:

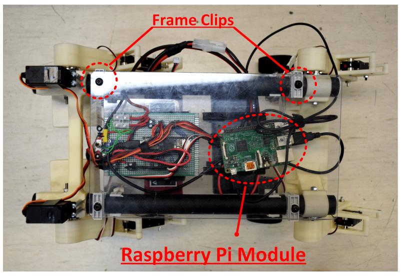
- **Adjustable Lever-Bottom Limb Angle:** By adjusting the relative angle between the actuation lever and the bottom limb, one can achieve different configurations. As a result, the robot can extend its legs in greater lengths or crouch even more. Students can see how the robot is able to carry bigger loads at the expense of reduced stability (closer to singular configurations) or smaller loads with increased stability while crouching (Fig. 3a).
- **Different Lever Options**: By adjusting the lever length, one can focus on the effect of either higher speed or force. By placing the linear actuator further or closer to the knee joint, students can observe in real time the trade-off between force and speed, and the effect of the robot's legs on the active workspace (Fig. 3b).
- **Carbon Tube Frame:** A lightweight body of adjustable length is designed, which also gives the instructor the ability to add or remove modules from the robot using clip-on components (Fig. 3c). These modules include alternative microcontrollers, sensors, cameras or even different motor housings.



(a) Adjustable Lever Angle.



(b) Different Lever Options.



(c) Carbon Tube Frame.

Fig. 3: The three core modularity mechanisms of the robot. By incorporating these mechanisms into the design, the robot is becoming more versatile on how it can be used in a lecture.

Finally, to steer the robot when moving on wheels, it was decided to simulate the Ackermann Steering method [18] by incorporating two vertical Degrees of Freedom (DOFs) into the two front legs. In this way, one can control the Yaw angle of each leg independently. These two DOFs give the students the opportunity to program a virtual Ackermann Steering mechanism and experience the importance of achieving the no-slip condition proposed by this steering method. This method is widely used when driving wheeled vehicles such as mobile robots or even more commonly commercial cars.

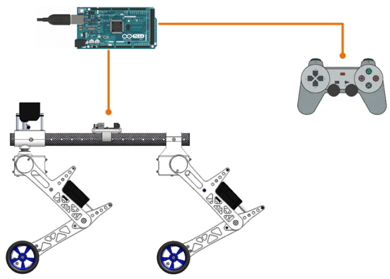
2.2 Electronics and Control

The robot incorporates 14 Hobby Servo Motors: 4 RC servos for the hip joints, 4 linear actuators for the knee joints, 4 continuous rotation servo motors for the wheels, and 2 RC servos for the steering DOFs. All the robot's actuators share the same control protocol using Pulse Width Modulation (PWM) signalling. The entire system is powered by an 8V Li-Po battery mounted on the body.

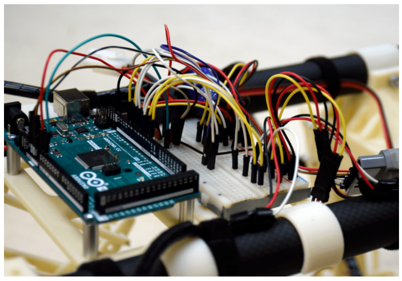
Maera is a teleoperated robot, which means that there are no sensors mounted on the robot's body or the limbs, providing feedback for autonomous functions. The students can control the robot's movement by programming an appropriate microcontroller. In detail, they can control the robot's posture, driving speed and steering angle by sending PWM signals to the corresponding actuators. The current version of the robot can be teleoperated using two different methods.

1) **Arduino Mega:** The Arduino Mega [19] is a popular microcontroller board, very common amongst hobby makers and educational robotics instructors. It features 14 Output Pins capable of producing PWM Signals, 16 Analog Input Pins, 16MHz Clock Speed, 256kb Flash Memory (current sketch uses 5kb) and 8kb of SRAM (current variables use 0.5 kb). Each motor's signal cable is connected to one of the 14 PWM pins and the students can send commands to the microcontroller using a Playstation Controller [20]. Prototyping tools such as a breadboard and jumper cables are used so that the students can see how everything is wired on a basic circuit or experiment with alternative connections themselves (Fig. 4a, 4b).
2) **RPi & Teensy 3.5:** The Raspberry Pi (RPi) [21] is a complete Linux-running micro-computer, or better known as a Single Board Computer (SBC). The students can connect to the Raspberry Pi using WiFi and Secure Shell (SSH) Network Protocol and send commands using their computers or smartphones. The Raspberry Pi then runs a Python program to communicate with a microcontroller board called Teensy 3.5 [22] using the UART (Universal Asynchronous Receiver/Transmitter) protocol (Fig. 4c, 4d). The Teensy is a powerful, feature-rich, Arduino-programmable microcontroller board, which is also tiny and of low cost. Here, the Teensy replaces the Arduino used in the first setup, since it is able to produce the PWM signals necessary to drive the actuators. Using this control framework the students can work with a setup widely used in complex robots that typically need the combined power of one (or more) Linux-based computer(s) for computationally intensive tasks, and one (or more) microcontroller(s) for low-level signal handling.

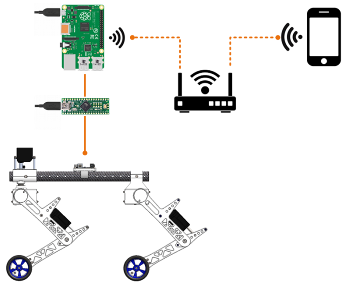
The programming scripts used in the aforementioned setups are based on a simple input/output open-loop logic and can be made available upon request.



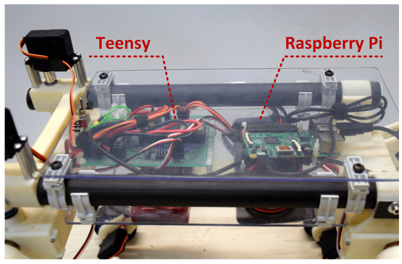
(a) Arduino Circuit.



(b) Arduino Mounting.



(c) Raspberry Pi Circuit.



(d) Raspberry Pi Mounting.

Fig. 4: (a),(b) The students can either use an Arduino board and drive *Maera* using a controller or (c), (d) they can use a Raspberry Pi SBC and a Teensy 3.5 board to drive the robot wirelessly by connecting their smartphones to a registered IP Address.

To conclude, *Maera* has been built in a way that allows an instructor to explain the different stages of the design process and the principles of legged robots. For example, during a lecture one can showcase kinematic principles through the leg design. The different stages of the development of the legs, from idea to final product, can be explored and the conceptual design process validated, by presenting different simulation and experimental results.

3 Educational Use-Cases

In this section, the different use-cases proposed for the robotic platform *Maera* are discussed. The robot can be used as an educational platform for Design and Robotics courses, a simple and easy to control platform on which students can work their thesis on, as well as a tool to communicate the field of legged robotics to the general public through short educational events. The use-cases in which the robot has been used already include the following.

3.1 NTUA-UDE Summer School

The NTUA-UDE Summer School was the final project of a 3-year collaboration between the NTUA and the UDE. It took place at the premises of NTUA's School of Mechanical Engineering from 2/9/2019 to 11/9/2019. The summer school was attended by 23 engineering students (13 German and 10 Greek). During the summer school, *Maera* was used as an educational aid for the lectures (L) and workshops (W) as presented in Table 1.

Table 1: Robotic platform usage in lectures (L) and workshops (W).

Title		Description
MSC Adams	L	Used part files to simulate the dynamic behaviour of the robot on MSC Adams.
Design of a Hybrid Legged Robot	L	Used the robot as an example of how to design legged robots and what are the main principles of such systems.
Introduction to 3D Printing	L	3D Printing principles and design rules showcased on the robot's structural parts.
Introduction to Embedded Systems	L	Using Microcontrollers to control robots and their main principles.
3D Printing the Robot	W	The students prepared the files and printed the necessary parts for the robot.
Assembling the Robot	W	The students assembled the printed legs so they would be functional. During that time they tackled real-life manufacturing constraints while using different tools and joining/fitting methods.
Controlling the Robot	W	Together with the lecturer, the students programmed and controlled the robot.

The lectures were taught in a sequence that presented the entire design process of the robot. During the lectures, the students would delve into the theoretical knowledge needed to complete each design phase and with the help of the physical robot see how each principle was implemented. Firstly, the students attended a lecture in which the MSC Adams simulation software was presented. During that lecture, CAD files of the robot were used to represent the different links and joints. In this way, students could simulate the dynamic behaviour of the robot in a real-life operation scenario (Fig. 5a). Next, a lecture was given on the principles of hybrid legged robots, where the students had the chance to see the effect of each decision made during the design process, e.g popular ways to mount wheels or the importance of leg length in legged robots. During the Introduction to 3D Printing lecture, major 3D Printing principles were presented. The students could inspect the robot and identify which principle was used while designing each part, for example layer orientation, joining methods, etc. Finally, the students attended a lecture on Embedded Systems, where they learned how to use different computing platforms to control their own robots.

After the lectures, the students attended three workshops where they used the knowledge gained to 3D print, assemble and control the robot *Maera*. The workshops followed the sequence presented next.

1) The students were instructed on how to use the lab's 3D Printer and prepared the printing jobs for two legs. They oriented and arranged the parts and then initiated the printing process.
2) After printing was finished, students were divided into two groups to assemble the legs under the supervision of staff. Each group was given printed instructions, blueprints, and the necessary tools and components to fully assemble one robotic leg (Fig. 5b).
3) After assembling the legs, the students mounted them on the existing robot and in cooperation with the lecturers, managed to drive the robot. This was done in two ways. One way was to use the Arduino module where they assessed the code and drove the robot around the classroom using a joystick. The other way was to use the Raspberry Pi module where 3 students connected their smartphones to the robot and managed to drive it by sending separate commands (Fig. 5c). One student was responsible for propulsion, one for steering, and one for controlling the leg configurations.

(a) MSC Adams simulation. (b) Assembling the robot. (c) Controlling the robot.

Fig. 5: (a) After simulating the robot's dynamic behaviour, (b) students worked together to 3D Print and assemble a working set of legs. (c) By mounting the legs and controlling the robot, they were able to be part of the design and control process as well as apply their knowledge to a hands-on project.

3.2 Researcher's Night - Short Event

Researcher's Night is an annual short educational event organized by NTUA, where research labs and teams inform the general public about their field of research and their advances. During the Researcher's Night 2019, *Maera* was presented to the public as a working prototype and a hands-on example for the field of legged robotics. The robot was controlled wirelessly and could adjust its height while rolling on the team's desk (Fig. 6). During the event, lab members were using the platform to introduce concepts like leg kinematics, the necessity of legged robots, actuation methods and more to the audience. Primary School, High School, and University Students as well as parents, enthusiasts, and National Television covering the event, were really intrigued by the robot.

Fig. 6: *Maera* can be used for short educational events as it is easy to carry and can be controlled wirelessly while a Li-Po battery powers the whole system.

4 Student Feedback

The students who participated in the NTUA-UDE Summer School Workshops were given an anonymous questionnaire that measured their overall appreciation of the teaching methods involving *Maera*. They were asked 14 closed-type questions and each student provided their answer on a 7-level Likert scale. Furthermore, the students were asked one open-type question about their opinion of this teaching method, its strengths, and ideas for improvement. The questions used in the questionnaire were adapted from previous research [23] and modified accordingly (Table 2).

Table 2: Questions given to students to answer on a 7-level Likert scale.

No.	Question
1	...helped me better understand theoretical Engineering concepts...
2	...increased my level of familiarity with Mechatronics...
3	...increased my desire to pursue Mechanical Engineering as a profession...
4	...helped me decide which area in Mechanical Engineering I want to pursue...
5	...helped me apply theoretical knowledge to real-life applications...
6	...helped me better understand the Engineering Design process...
7	...helped me gain knowledge I was initially unfamiliar with...
8	...increased my level of attention during the lectures I attended...
9	...helped me develop my abilities and skills for the subject of Mechatronics...
10	...helped me develop my ability to think critically about Mechatronics...
11	...encouraged me to work as part of a team in the spirit of cooperation...
12	...to complete the various tasks I collaborated with my teammates/instructor...
13	Overall, my team worked effectively together on this project...
14	Considering both the limitations and possibilities of the subject matter and the course, how would you rate the overall effectiveness of this teaching method?

The answers provided by the students are summarized in Fig. 7. The mean value and the corresponding standard deviation for each question are calculated and presented in the form of a histogram. On a scale of 1 to 7, the students graded this teaching method very positively and this attitude was evenly distributed among them. With a mean value of 6.17 and a standard deviation of 0.76, it is clear that *Maera* was well received by the students as an educational platform.

From the lecturers' perspective, the students were more actively engaged in the theoretical concept whenever a hands-on stimulant was introduced in the teaching process. During the summer school, the students could easily apply the theoretical knowledge they gained on real-life problems and systems that they were presented with. This heightened their interest to pursue further study as they were really intrigued by the robot and seemed eager to learn more about its working principles.

When asked about their opinion on this teaching method's strengths and ideas for improvement, most of the students highlighted the fact that during their everyday university courses, they do not have the opportunity to tackle real-life problems. An example of answers received for the open question is presented next, as quoted by one of the students.

"You will forget 90% of theory you get from lectures, but practical knowledge provided by this teaching method will remain." (Anonymous, NTUA-UDE 2019)

Some of the students proposed a more robust control framework so that the robot could achieve more tasks. Indeed, that would let the students better understand what is required by the robot to tackle each task separately and is something that we are working on for future courses.

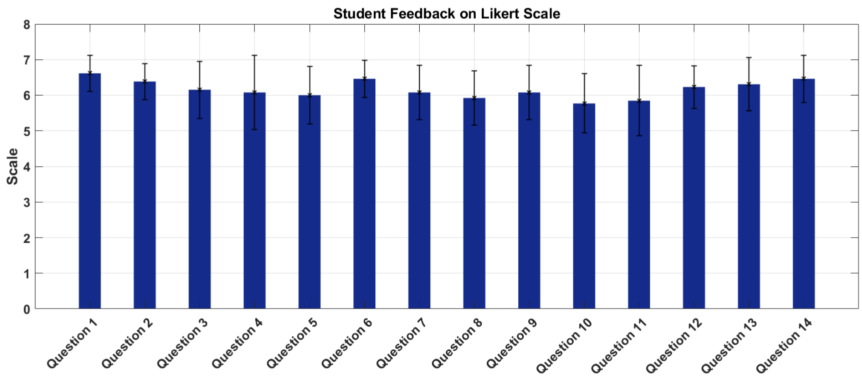


Fig. 7: The average answers provided by the students on a 7-level Likert scale show that the robot was successful as an educational platform and helped the students better realize theoretical concepts taught during the summer school.

5 Conclusion and Future Work

This paper presented the robotic platform *Maera* as a quadruped robot aimed for education and research. The robot can be used as a teaching tool in the education curriculum, as well as a research platform for students to work on. The design is focused on the educational aspect, as it incorporates various features aiming to engage the students in an interactive learning experience. The robot can work as a hands-on example to accompany different engineering lectures, taking students through all stages of a legged robot's life. Great emphasis is given on the design and manufacturing of the robot, as opposed to the almost exclusive use of educational robots as examples for control methods for completing various tasks. In this way, students interested in different fields of engineering can obtain useful practical knowledge. By using the robot in two separate use-cases, we reached the conclusion that *Maera* is a successful platform in introducing legged robotics to the general public. When *Maera* was used as a teaching tool, students showed increased interest in the theoretical knowledge derived from each lecture. Thus, proving to be a very efficient method of inviting students to further explore the field of mechatronic systems such as legged robots.

As the first prototype of the robot was used successfully in the curriculum, we plan on making the robot completely open-source, with instructions so that anybody can replicate it. Furthermore, a more robust teaching framework in the form of a course plan will be designed to accompany the robot in the educational process. Finally, we are thinking about utilizing sensors to introduce autonomy in the teaching process, as well as modifying the leg design so that the robot can be built by using only conventional hobby servo motors. Such a design can lower the cost and broaden the audience that can adapt *Maera* as a teaching tool. With this platform, we hope to introduce legged robotics to the educational community and bridge the gap between practical application and theoretical knowledge.

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